A new reference section for the Toolonga Calcilutite, Carnarvon Basin, Western Australia

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Abstract

A detailed description of a reference section of the Toolonga Calcilutite within the type area, lower Murchison River valley, Western Australia is presented. An 18.5 m section of white *Inoceramus* calcarenite, sandy calcilutite and greenish calcilutite, comprising three easily identifiable lithostratigraphic units, 1.5 km west of the type section at latitude 27°35′54″S longitude 114°12′42″E was selected for study. The stratigraphic distribution of benthonic macrofauna, and 98 foraminiferal and 6 calcareous nannoplankton species is documented. Analysis of the faunal characteristics shows that the Toolonga Calcilutite was deposited in warm temperate, normal-salinity ocean waters of outer neritic to upper bathyal depths. The reference section encompasses the *Heterohelix papula* through *Globotruncana arca* planktonic foraminifera zones and the *Reinhardtites anthophorus* through *Aspidolithus parcus* calcareous nannoplankton zones indicating that the Toolonga Calcilutite is early Santonian to early Campanian in the type area.

Introduction

The Toolonga Calcilutite is the oldest Cretaceous chalk unit recorded in the onshore Carnarvon Basin and includes Santonian and Campanian strata. The formation is exposed in the Murchison River area, where it forms the upper unit of the Cretaceous succession (Clarke and Teichert 1948), and in the Hamelin Pool and Giralia Anticline areas where it is overlain by younger Cretaceous units (Hocking *et al.* 1987). An equivalent of the Toolonga Calcilutite, the Gingin Chalk, is recognized in the Perth Basin to the south of the study area (Feldtmann 1963, Playford *et al.* 1976, Rankin 1987).

This paper provides a detailed description of the lithostratigraphy, biostratigraphy and age of the Toolonga Calcilutite in the type area, lower Murchison River valley, and in particular records the distribution of foraminiferal faunas and age diagnostic calcareous nannoplankton encountered in closely spaced samples from a continuously exposed section of the Toolonga Calcilutite.

Clarke and Teichert (1948) named and described the 'Toolonga Chalk' and 'Second Gully Shale' in the Murchison House Station area. Later mapping by Johnstone *et al.* (1958) showed that the 'Second Gully Shale' could not be recognized consistently in the type area so both formations were placed together and named the Toolonga Calcilutite. The type section of the Toolonga Calcilutite was designated by Johnstone *et al.* (1958) based on their mapping of the southern Carnarvon Basin for West Australian Petroleum. The location of the type section is recorded on a series of aerial photographs used in the mapping and now held at the Geological Survey of Western Australia. The type section consists of a 26 m (85ft) thick succession of cream chalk and greenish calcilutite (Johnstone *et al.* 1958, Condon 1968 and Hocking *et al.* 1987). In the early literature there has been some confusion in the cited latitude and longitude positions of the type section and of nearby landmarks. This was clarified by Hocking *et al.* (1987) who positioned the type section location at latitude 27°36′00″S longitude 114°13′40″E, 2 km north northeast of Yalthoo Spring as shown here on Figures 1 and 2.

During field mapping and sampling for this study the area near Thirindine Point containing the type section was searched for suitable sections but slumping and weathering had obscured some of the outcrop here. A continuous section of the Toolonga Calcilutite was found approximately 1.5 km west of the type section locality. This reference section lies at latitude 27°35′54″S longitude 114°12′42″E, [Grid Reference 245441] as marked on the Gantheaume 1:100 000 topographic sheet (Edition 1) (Figure 1, 2) and represents the most complete section in the type area at the time of study. This study is based on the reference section.

Methods

Thirty eight samples were selected for grain-size distribution. Each sample was dried, weighed and wet-sieved through a 63 m sieve and the 63-2 000 µm fraction dried and weighed. To determine impurities, a composite sample of material from differing levels of the section, was placed in dilute hydrochloric acid (2 wt. %) to remove carbonate. Supernatant liquid was periodically replaced with fresh acid until effervescence ceased. The insoluble residue was filtered, washed to remove $CaCl_2$, dried and weighed. Analysis showed it to be a K, Na, Mg, Ca, Al, Fe silicate and therefore probably glauconitic clay.

To record planktonic foraminifera in the section, thirty-eight samples, collected at 50 cm intervals from the base of the section, were wet-sieved, dried and the 63-2 000 μm fraction examined. Abundances of planktonic foraminiferal taxa were visually estimated because infraspecies morphological variation made the quantitative abun-

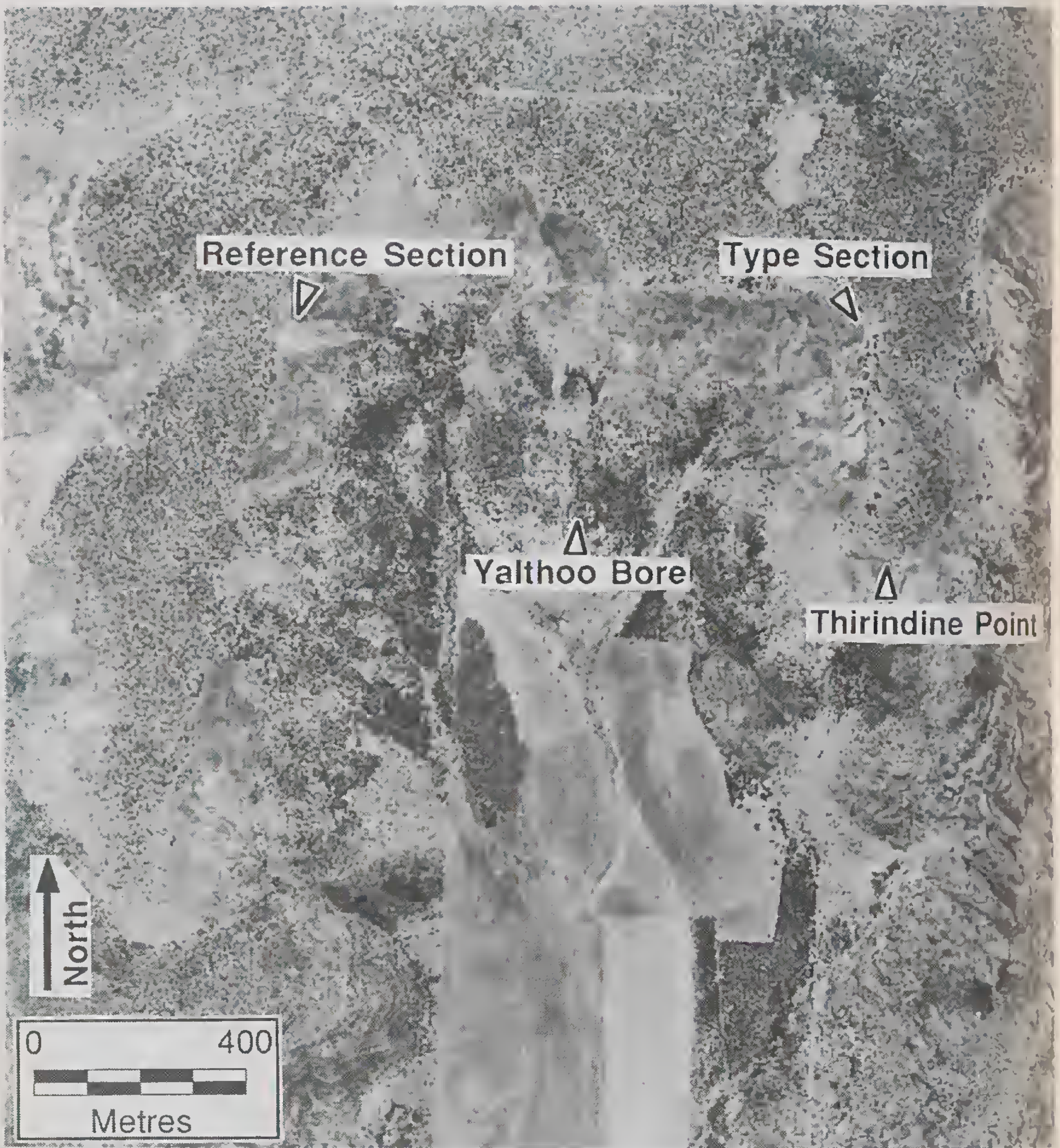

Figure 1 Aerial photograph of the lower Murchison River area showing the position of the reference section (enlargement of Photo. 5077 AJANA Run 11 [5043-5080] reproduced with permission of the Department of Lands Administration).

dance determination of some forms difficult. Thirteen of the samples were chosen at about two metre intervals to provide a record of the benthonic foraminifera. The 150-2 000 µm fraction of these samples were systematically picked and the numbers of specimen from each benthonic taxon was counted.

To provide additional age control in the section, strew slides containing abundant calcareous nannoplankton also were prepared from fresh material taken from the same levels as those systematically studied for foraminifera.

Lithostratigraphy

In the type area, the Toolonga Calcilutite disconformably overlies the Alinga Formation (Figure 2). Clarke and Teichert (1948) and Johnstone *et al.* (1958) placed the contact at the abrupt change in lithology from green glauconitic sandstone and siltstone to cream-coloured chalk where a thin but extensive layer of ovoid phosphatic nodules, which range from 3-10 cm in diameter, is present (Figure 3). The phosphatic nodule layer indicates very low sedimentation rates or an erosive event (Ames 1959, Kennedy and Garrison 1975, Kennett 1982) and suggests a disconformity between the underlying Alinga Formation and the Toolonga Calcilutite. Copp (1987) suggested that the Alinga Formation may extend into the Middle Turonian or younger in the type area based on the presence of biostratigraphically-useful calcareous nannoplankton recorded from the top of the Alinga Greensand, which indicates that the disconformity may range from Late Turonian to Early Santonian. The top of the Toolonga Calcilutite is covered by soil and calcrete and no contact with younger units is seen in the study area. The section is composed of three conformable lithostratigraphic units (Figure 3) which are distinctive in outcrop due to differing induration, colour and composition as described below. Units 1 & 2 may represent the 'Toolonga Chalk'; and Unit 3, the 'Second Gully Shale' of Clarke and Teichert (1948).

Unit 1. This disconformably overlies the Alinga Formation, is 50 cm thick and consists of fine-grained, glauconitic sand and white calcilutite. The glauconitic grains, 0.1-0.5 mm in diameter, have undulose irregular outlines indicating an authigenic origin. Some grains are globular which may indicate that they formed within foraminiferal tests. These contrast with the glauconite particles of the underlying Alinga Formation which are well rounded, apparently from being continually reworked and rolled along the bottom. Fish teeth are common in the lowest part of the unit. They are composed of insoluble phosphatic material (mainly apatite) and therefore would be concentrated by early selective dissolution of the nannoplankton / foraminiferal ooze on the seafloor.

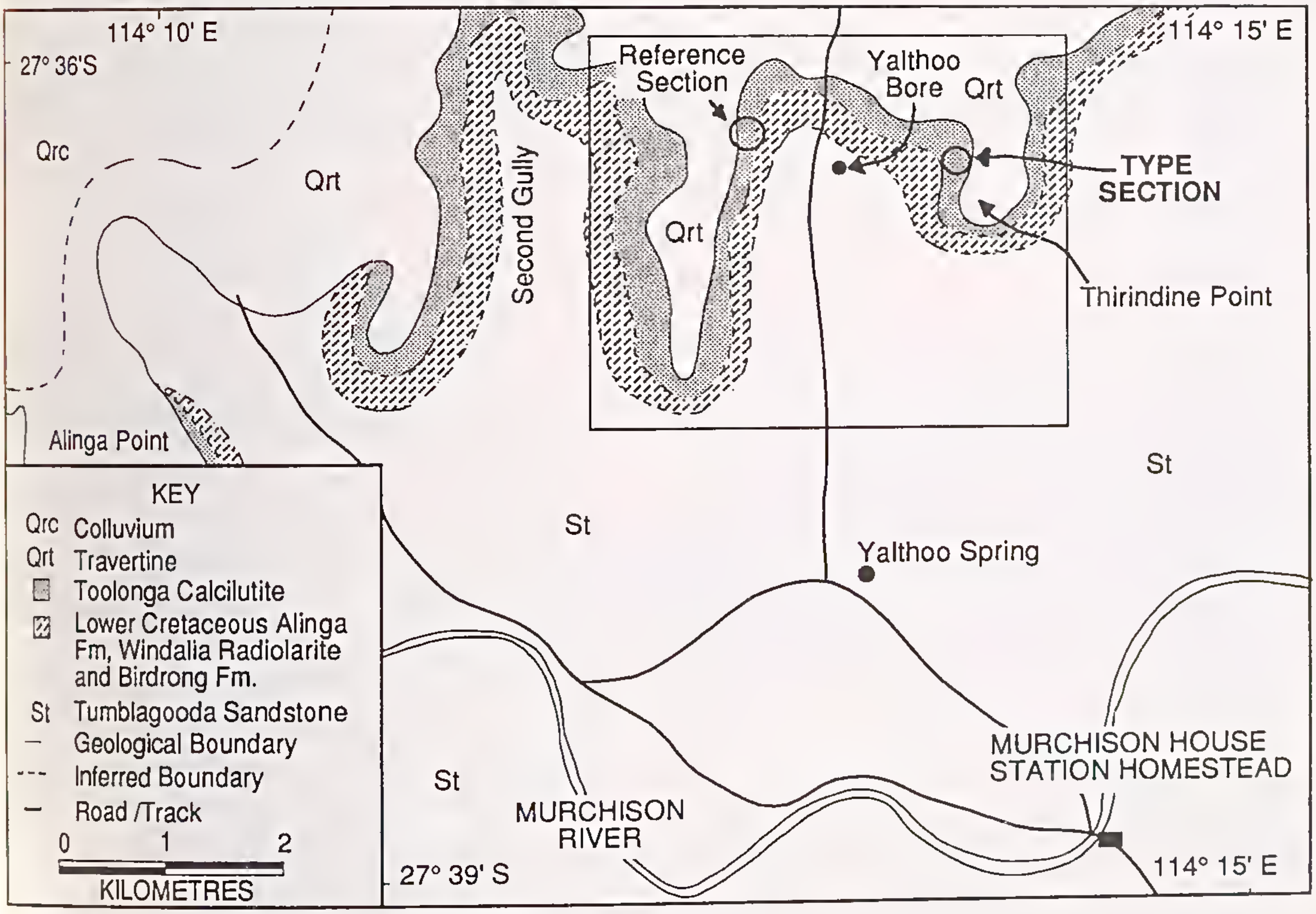

Figure 2 Geological map of the lower Murchison River area.

Unit 2. Conformably overlying Unit 1 is 8 m of white calcilutite and *Inoceramus* calcarenite characterized by an abundance and diversity of macrofossils. Fragments of *Inoceramus* are common as discontinuous bands 1-95 cm thick or as single randomly orientated specimens. Calcite prisms derived from the breakdown of *Inoceramus* are common constituents of the calcilutite and compose more than 50% of the 63-2 000 µm fraction in many of the samples. Individual peaks of sand-sized material seen in Unit 2 (Figure 3) correlate with *Inoceramus* rich horizons. Light yellow-brown phosphatic nodules, 1 cm in diameter, are present in three laterally extensive horizons 1 m, 2.9 m and 8.5 m above the phosphatic nodule horizon marking the Alinga Formation–Toolonga Calcilutite contact.

Unit 3. Conformably overlying Unit 2 is a 10 m section of marly greenish calcilutite. Unit 3 differs from Unit 2 in being less indurated. The greenish appearance of Unit 3 arises from the high proportion of glauconitic clay within the calcilutite. It is covered by weathered calcilutite and soil, and appears homogeneous due to intense bioturbation (which has obscured many of the smaller-scale features of bedding) and the lack of large *Inoceramus* fragments common to Unit 2. Calcite prisms derived from *Inoceramus* are rare in the first 2 m of Unit 3 and are absent above this level. A single, laterally extensive bed of chert nodules occurs 7.5 m above the Unit 2–Unit 3 boundary. The nodules are generally small and ovoid, although rare specimens are tabulate and up to 20 cm across. Chert nodules form more than one horizon in other exposures of the upper unit of the Toolonga Calcilutite within the area. When broken, the nodules consist of alternating light and dark brown layers of chert and minor inclusions of silicified chalk.

Chert nodules form by the early diagenetic replacement of carbonate by opaline silica below the sediment surface, and their shape depends on the morphology of the oxic-anoxic mixing zone (Clayton 1983, Maliva and Siever 1988). Because burrows alter the homogeneity of the sediment and the shape of the mixing zone, chert nodules are likely to develop within burrow forms (Bromley and Ekdale 1983, Clayton 1983, Felder 1983). Chert nodules in the type area are generally digitate or tabulate. Digitate nodules are cylindrical, up to 50 cm long and 10 cm in

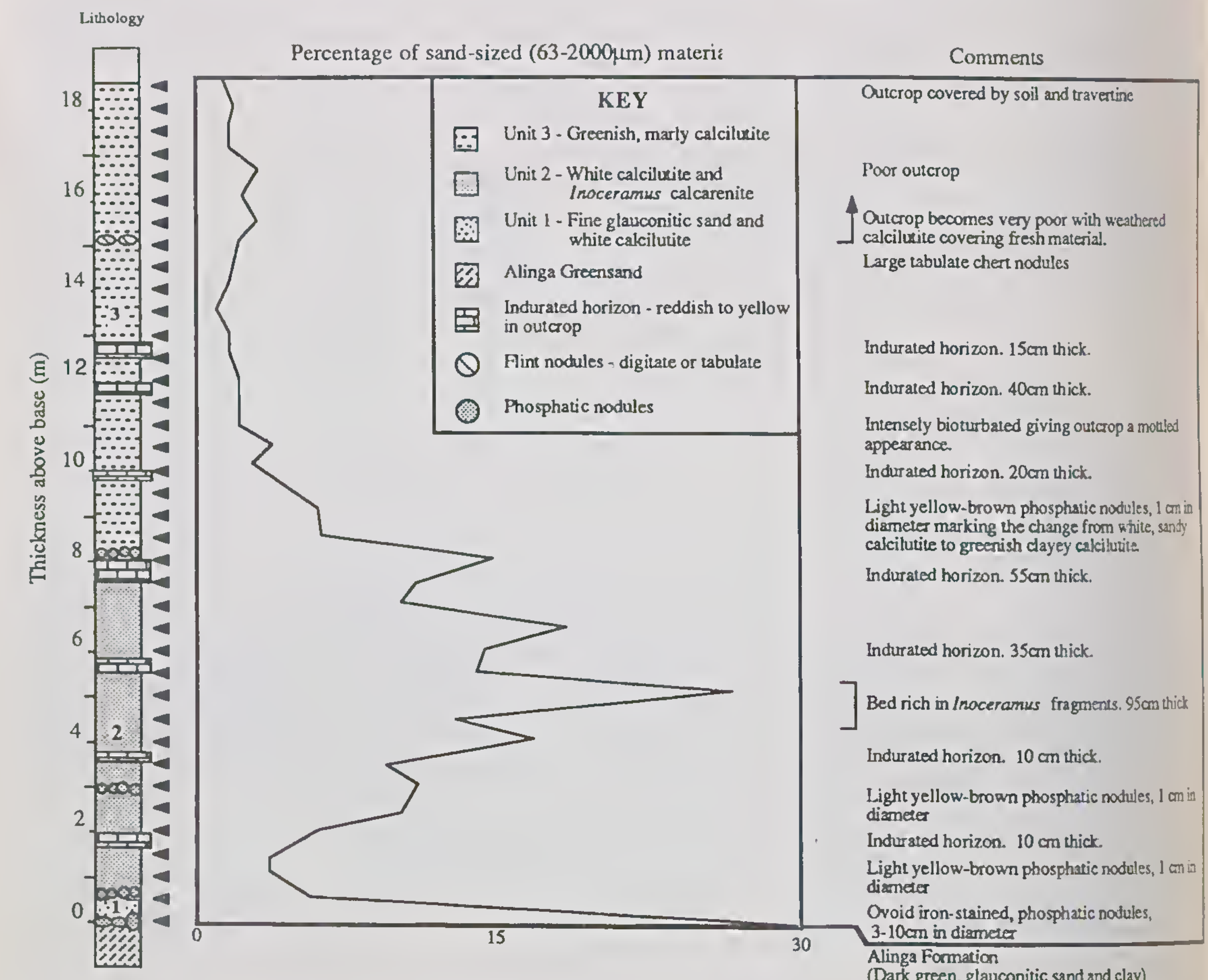

Figure 3 Lithostratigraphy of the reference section, Toolonga Calcilutite.

diameter, and tend to be perpendicular to bedding and appear to mimic other features seen in the Toolonga Calcilutite which are thought to have formed by the burrowing activites of irregular echinoids. Tabulate nodules are about 3 cm thick, up to 20 cm across, generally oval shaped, parallel to bedding, and are commonly associated with indurated horizons which may have restricted the oxic-anoxic mixing zone along the plane of bedding creating favourable conditions for the formation of chert nodules. Digitate nodules occur mainly in heavily bioturbated horizons where burrows would tend to channel the mixing zone into other horizons.

Although indurated horizons are common in both Unit 2 and Unit 3 (weathering to reddish-yellow layers, 10-55 cm thick, across the outcrop at about 2 m intervals), there is no evidence that these were hardgrounds similar to those described in English chalks by Bromley (1967), Hancock (1975), Kennedy and Garrison (1975), Scholle (1977) and Jarvis (1980). The lack of animal borings, scouring, phosphatization or encrustation by sessile organisms associated with the indurated beds indicates that the indurated horizons were not exposed on the seafloor at any time.

Dissolution of the Toolonga Calcilutite is minor, with the exception of Unit 1 which is heavily affected and is most apparent in the foraminiferal assemblage which includes mainly robust, thicker-walled rotaliids and agglutinated foraminiferal tests. Keeled planktonic foraminifera are affected by dissolution in the lower half of the section (Units 1 and 2), and the thin-walled portion of many tests is absent. Samples which show most dissolution contain abundant *Inoceramus* prisms and other mollusc fragments. Ostracods generally do not appear to be much affected by dissolution. In Unit 3, surfical solution of the chalk has produced small pits infilled with insoluble clayey material similar to pits described by Scholle (1977) in the European chalks.

Biostratigraphy

Macrofossils are common at all localities of the Toolonga Calcilutite in the Murchison River area. Faunal elements identified by the author with assistance from Dr K. McNamara and Mr. G. Kendrick of the Western Australian Museum are the serpulid worm *Serpula fluctuata* Sowerby; brachiopods *Trigonosemus acanthodes* Etheridge, *Magasella cretacea* Etheridge; bivalves *Pycnodonta gingimensis* Etheridge, *Inoceramus* sp., *Ostrea* sp.; crinoids *Marsupites testudinarius* (Schlotheim), *Marsupites* sp., *Uintacrinus* sp. A number of trace fossils, cidaroid echinoid spines and barnacles were recorded from the reference section but have not been identified to generic level.

Inoceramus occurs as (a) solitary, randomly orientated fragments or (b) 1-95 cm thick, laterally discontinuous horizons which appear to be lag deposits created by localized current activity as evidenced by their horizontal alignment and sorting. Entire valves are very rare and only two specimens were found in the type area. The larger *Inoceramus* clasts are confined to Unit 2, and only microscopic fragments and prisms are present in the lowest few metres of Unit 3. No fragments of *Inoceramus* were found in Unit 1.

Ossicles of the crinoid *Uintacrinus* are common in the lower half of the section where they form a clearly defined zone 2.5 m-5.5 m above the base of the section. No calicular plates identified as *Uintacrinus* were found in any of the exposures in the area. *Marsupites* calicular plates were found in sections throughout the area and form two distinct groups according to their size, ornamentation and distribution. The smaller, smooth form appears sporadically below the *Uintacrinus* zone and could not be identified to species level. The larger form, having radial striations on the upper surface, was tentatively identified as *Marsupites testudinarius* (Schlotheim) and occurs only above the *Uintacrinus* zone. Clarke and Teichert (1948) reported two species of *Marsupites* from the Toolonga Calcilutite in the Murchison River area: a smaller form resembling *Marsupites testudinarius* (Schlotheim) and a considerably larger, smooth, second type of plate. No specimens of this second form were found.

The oyster *Pycnodonta ginginensis* Etheridge is found throughout the section, most commonly as solitary specimens with an inflated dorsal valve, orientated parallel to bedding. Very rare, immature specimens were found attached to *Inoceramus* fragments.

Bioturbation is common throughout the section and three burrow forms are present. The first form is cylindrical, 1-2 cm in diameter, infilled with coarse-grained sediment. These burrows extend for 2-10 cm across the outcrop and are generally sub-parallel to the bedding. Their morphology indicates that they may have been formed by irregular echinoids. The second burrow form is common throughout the section, and consists of randomly oriented, cylindrical burrows about 1 cm in diameter which can be traced for 10-60 cm. The third burrow form is common in the upper part of the section and in the topmost 30 cm of the Alinga Formation It forms a branching meshwork of burrows, 1-2 mm in diameter and 1-5 cm long. All three forms appear to have be created by deposit feeding organisms.

Other macrofossils (such as the serpulid worm *Serpula fluctuata* Sowerby, brachiopods *Trigonosemus acanthodes* Etheridge, *Magasella cretacea* Etheridge, and the bivalve *Ostrea* sp.) appear to be randomly distributed within the section.

The section contains an abundant and diverse assemblage of generally well-preserved foraminifera. Planktonic foraminifera dominate the succession, with the exception of the lowest sample, and form 33-74% of the systematically-picked assemblages. The percentage of planktonic foraminifera rapidly rises from less than 1% in the lowest sample to about 65% 4.5 m above the base of the section. The abundance of planktonic foraminifera remains near this level until 14.5 m above the base, then gradually declines to 40% in the uppermost sample. The Globotruncanacea, Planomalinacea and Rotaliporacea are the dominant planktonic superfamilies; the Heterohelicacea are less common. The stratigraphic distribution of planktonic foraminiferal species is shown in Figure 4 and Table 1. Most of the forms are wide-ranging but notable exceptions are *Heterohelix papula* (Belford) and *Hastigerinoides simplex* (Morrow) which only occur in the first few metres of the section; *Globotruncana fornicata* (Plummer) ranges from 3.5-6.0 m and *Globotruncana arca* (Cushman) which ranges from 7.5-18.5 m. Another short ranging form, *Globotruncana* sp. (5.0-7.5 m) appears to be transitional between *G. fornicata* (Plummer) and *G.arca* (Cushman) but further work is required to examine any evolutionary trend.

Benthonic foraminifera are also abundant and diverse in the section. The stratigraphic distribution of benthonic foraminifera is shown in Table 2. The Order Rotaliida (Haynes 1981) dominates the assemblage at all levels with abundances ranging from 10-25% of the total assemblage. Excluding the lowest sample where selective dissolution has concentrated foraminifers with more robust tests, rotaliids comprise 77% of the assemblage. Other orders contribute less than 20% of the total assemblage.

It can be seen from the stratigraphic distribution of benthonic foraminifera (Table 2) that some forms abound

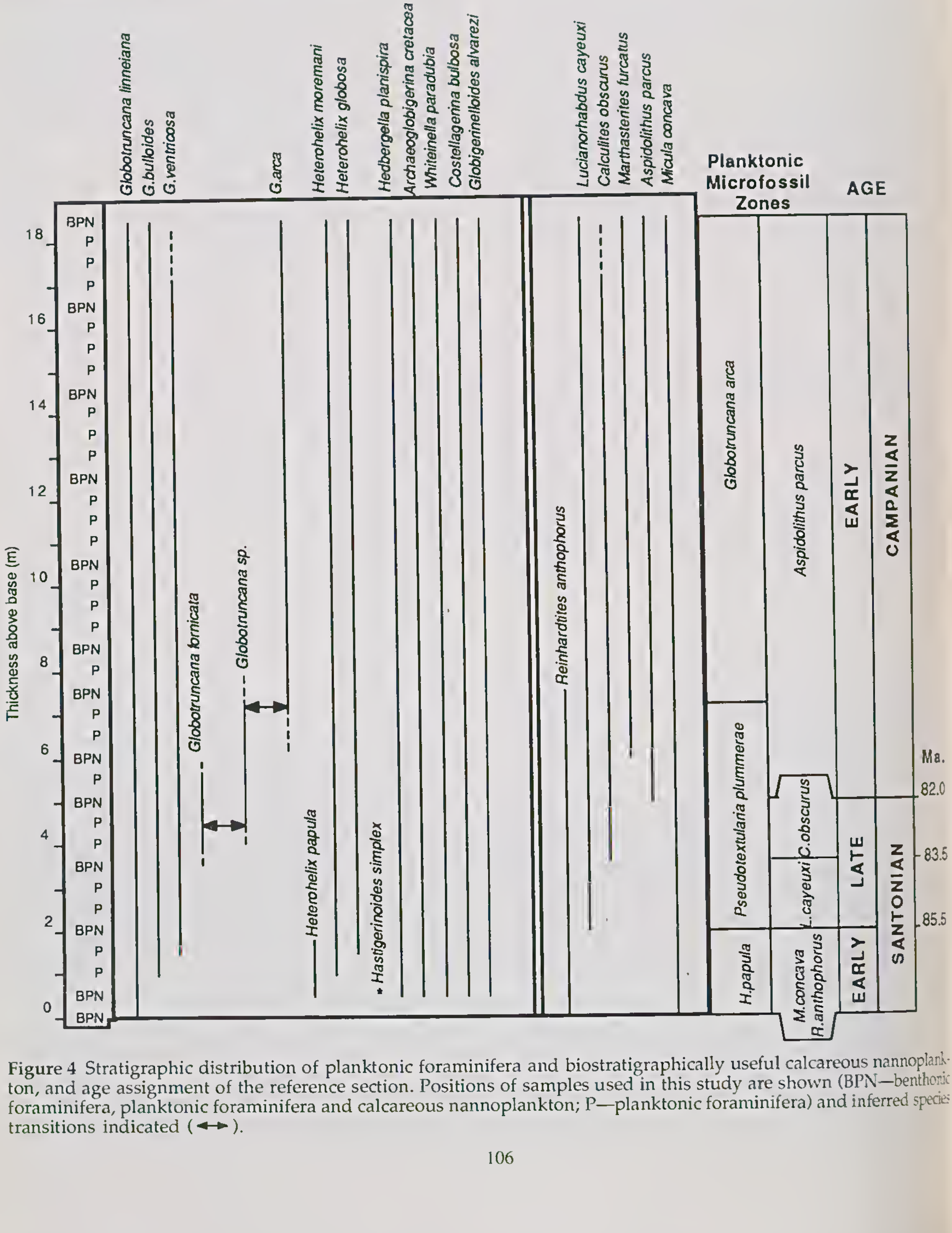

Figure 4 Stratigraphic distribution of planktonic foraminifera and biostratigraphically useful calcareous nannoplankton, and age assignment of the reference section. Positions of samples used in this study are shown (BPN—benthonic foraminifera, planktonic foraminifera and calcareous nannoplankton; P—planktonic foraminifera) and inferred species transitions indicated (◄►).

Table 1

Stratigraphic distribution of planktonic foraminifera in the reference section, Toolonga Calcilutite. Species are listed by superfamilies as defined by Loeblich and Tappan (1988). The abundance of each taxon is expressed as rare (R), common (C), abundant (A) in a systematic pick or present x in a selective pick only.

	UNIT 1		UNIT 2						UNIT 3				
	0.0	0.5	2.0	3.5	5.0	6.0	7.5	8.5	10.5	12.5	14.5	16.5	18.5
HETEROHELICACEA													
Heterohelix globulosa			C	R	R	R	R	R	R	R	R	R	R
Heterohelix moremani			R	R	R	R	R	R	C	C	R	R	C
Heterohelix papula		C	R										
PLANOMALINACEA													
Globigerinelloides alvarezi			R	R-C	x	x	R	x	R-C	R-C		R-C	R
Hastigerinoides simplex		x											
ROTALIPORACEA													
Costellagerina bulbosa			R-C	R-C	R-C	R	x	x	R	R	R	R	
Hedbergella sp. aff. *H. planispira*		x	C	R	R	R	A	C	C	C	R	R	R
Whiteinella paradubia		x	C	R-C	R-C	C	R	x	x		R	R	R
GLOBOTRUNCANACEA													
Archaeoglobigerina cretacea		x	x	x	R	R	R		x	x	x		R
Globotruncana sp.					R-C	R	x						
Globotruncana arca							R	R	R	R	R	R	R
Globotruncana bulloides		R-C	R-C	R-C	R-C	C	R	R	R	x	x	x	x
Globotruncana fornicata				x	R-C	x							
Globotruncana linneiana	R	A	A	A	C	R-C	R	R-C	R	C	R	R	R
Globotruncana ventricosa			x	R	R	R-C	R	R	R	x	x	x	

within the reference section and have similar distribution patterns. These distribution patterns fall into three rough categories. The first group has abundances which are greatest in the lowest parts of the section (Unit 1) and include *Anomalinoides undulatus* Belford, *Clavulinoides trifidus* Belford, *Gaudryina* sp. cf. *G. laevigata* Franke and *Notoplanulina* sp. *Globorotalites micheliniana* (d'Orbigny), *Gyroidinoides noda* (Belford), *Lingulogavelinella insculpta* (Belford), *Marssonella oxycona* (Reuss), *Osangularia* sp., *Verneuilina parri* Cushman and *Pyramidina szajnochae* (Gryzbowskii) form the second group which have the greatest abundance in the middle of the section (Unit 2). The third is those forms which are most abundant within the upper half of the section (Unit 3): *Anomalinoides erikdaleusis* (Brotzen), *Dorothia bulleta* (Carsey), *Eponides concinna* Brotzen, *Eponides diversus* Belford, *Goësella chapmani* Cushman, *Pullenia cretacea* Cushman, *Spiroplectammina gryzbowskii* Frizzell, *Spiroplectammina paula* Belford.

The species distribution described above is thought to be environmentally controlled. Unit 1 and Unit 3 were deposited under conditions where bottom waters were slightly depleted in dissolved oxygen as inferred by the low numbers of calcareous metazoans and the dominance of smaller burrows (Rhoads and Morse 1971, Savdra and Bottjer 1986). The level of dissolved oxygen was high during deposition of Unit 2 as shown by the abundance and diversity of calcareous macrofossils. Other differences in the foraminiferal assemblages may be related to bathymetry.

Calcareous nannoplankton abound throughout the reference section. Only the stratigraphic distribution of those calcareous nannoplankton essential for age determination is recorded (Figure 4), although the total assemblage probably consists of up to 60 species. The calcareous nannoplankton examined from the reference section are: *Aspidolithus parcus* (Stradner), *Calculites obscurus* Deflandre, *Lucianorhabdus cayeuxi* Deflandre, *Marthasterites furcatus* (Deflandre), *Micula concava* (Stradner) and *Reinhardtites anthophorus* (Deflandre). Their stratigraphic distribution is shown on Figure 4.

A list of foraminifera and calcareous nannoplankton identified from the reference section is given in Appendix 1.

Age assignment

A Santonian age for the Toolonga Calcilutite was inferred by Clarke and Teichert (1948) from the presence of the pelagic crinoids *Uintacrinus* and *Marsupites*. Integrated planktonic foraminifera and calcareous nannoplankton biostratigraphy has resulted in a detailed age determination for the Toolonga Calcilutite in the type area (Figure 4). Planktonic foraminifera and calcareous nannoplankton identified within the reference section enables application of the unpublished zonation of Rexilius (1984; Figure 5 herein). The calcareous nannoplankton zonation shown in Figure 5 has been modified from Rexilius (1984) to include the *Reinhardtites anthophorus* zone, *Calculites obscurus* zone and *Calculites ovalis* zone of Sissingh (1977). The base of the Toolonga Calcilutite contains the biostratigraphically important planktonic foraminifera *Heterohelix papula* (Belford), which Rexilius (1984) used as a zonal index for his *Heterohelix papula* zone (early Santonian) and the calcareous nannoplankton *Reinhardtites anthophorus* (Deflandre) and *Micula concava* (Stradner) he used as the zonal index species for the *Reinhardtites anthophorus* zone (early Santonian). Rexilius (1984) used the first appearance of *Rugoglobigerina rugosa* (Plummer) as the datum marking the base of his *Rugoglobigerina rugosa* zone (middle Campanian). The absence of *R. rugosa* (Plummer)

Table 2

Stratigraphic distribution of benthonic foraminifera in the reference section, Toolonga Calcilutite. Species are listed by superfamily as defined by Loeblich and Tappan (1988) and expressed as a percentage of the total benthonic foraminiferal assemblage. Stratigraphic thickness is given in metres above base of the Toolonga Calcilutite.

	UNIT 1		UNIT 2						UNIT 3				
	0.0	0.5	2.0	3.5	5.0	6.0	7.5	8.5	10.5	12.5	14.5	16.5	18.5
AMMODISCACEA													
Ammodiscus cretacea	..	..	..	..	..	..	..	..	..	..	..	x	
Glomospirella sp.	..	..	..	..	..	..	..	..	..	..	..	x	.
RZEHAKINACEA													
Silicosigmoilina sp.	..	1	..	..	..	..	..	x	x	x	x	..	..
LITUOLIDACEA													
Haplophragmoides sp. cf. *H. kirki*	1	x	..	..	..	..	..	..	..	..	..	..	..
Ammobaculites sp. A	..	..	x	..	..	..	..	..	..	..	..	..	..
Ammobaculites sp. B	..	x	x	x	x	..	..	x	x	x	..	..	..
SPIROPLECTAMMINACEA													
Spiroplectammina grzybowskii	..	2	x	..	x	..	2	5	..	9	6	10	4
Spiroplectammina laevis	..	..	..	..	..	x	x	x	3	3	x	3	2
Spiroplectammina pauli	..	..	..	..	..	..	..	x	x	3	11	6	4
VERNEUILINACEA													
Gaudryina sp. cf. *G. laevigata*	1	7	6	13	..	x	..	x	x	..	..	..	..
Spiroplectinata compressiuscula	2	1	..	..	..	x	x	..	..	..	..	..	..
Verneuilina parri	..	..	x	1	x	x	5	3	3	..	..	x	..
TEXTULARIACEA													
Clavulinoides trifidus	2	6	x	..	..	..	..	..	..	..	..	..	..
Dorothia bulleta	..	..	3	2	x	4	..	..	..	..	x	9	..
Goesella chapmani	..	x	1	1	x	x	x	4	3	5	4	4	5
Marssonella oxycona	6	10	20	14	6	4	7	x	16	8	6	x	2
MILIOLACEA													
Spiroloculina cretacea	..	..	..	..	3	..	..	x	..	..	x	..	.
NODOSARIACEA													
Astacolus sp. A	..	..	..	..	..	x	x	..	..	..	..	..	..
Astacolus sp. B	..	..	..	..	..	..	..	..	..	x	..	..	..
Berthelinopsis sp.	..	..	..	..	x	..	..	..	..	..	..	..	..
Bullapora laevis	..	..	..	..	..	..	..	x	x	..	..	..	..
Citharina geisendorferi	..	..	x	..	..	..	..	..	..	..	..	..	.
Citharina multicostata	..	x	x	..	..	..	..	..	..	..	..	..	..
Citharina suturalis	..	..	x	..	2	..	..	x	..	..	..	..	.
Dentalina admodicosta	..	..	..	..	..	..	x	x	..	..	..	x	x
Dentalina marcki	..	x	..	..	..	..	..	..	..	..	..	..	..
Frondicularia costulifera	..	..	..	..	2	..	3	..	..	..	..	..	..
Frondicularia disjuncta	..	..	x	..	..	..	..	..	..	..	x	..	..
Frondicularia mucronata	1	x	..	..	..	..	..	..	..	..	..	..	..
Frondicularia planifolium	..	..	..	1	2	..	..	..	..	..	..	..	..
Frondicularia verneuiliana	..	..	..	..	..	x	x	x	..	..	..	..	..
Frondicularia teuria	..	..	x	..	..	..	x	x	..	..	..	..	..
Globulina sp.	..	x	..	..	2	..	..	..	..	..	..	..	..
Laevidentalina cylindroides	..	..	x	..	2	..	x	x	..	..	x	x	..
Laevidentalina gracilis	..	..	..	..	..	..	x	..	x	..	..	2	x
Laevidentalina luma	..	..	x	..	2	..	x	x	..	x	x	..	..
Laevidentalina sp.	1	..	x	1	..	x	..	x	..	..	x	..	..
Lagena hexagona	..	..	..	..	..	..	..	..	..	..	..	..	
Lagena sp.	..	..	..	..	3	..	..	..	..	..	..	..	..
Lenticulina macrodiscus	..	..	1	..	2	..	..	..	..	..	..	..	..
Lenticulina rotulata	2	..	..	..	3	x	x	x	3	3	x	..	x
Lenticulina sublobatus	..	..	..	1	2	..	..	..	..	..	..	..	..
Lenticulina sp.	3	3	3	2	2	..	..	x	x	..	x	..	x
Marginulina sp.	..	..	x	4	..	..	..	..	..	..	..	..	..
Neoflabellina praereticulata	..	..	..	..	..	..	..	..	x	x	x	x	x
Neoflabellina rugosa	..	..	x	2	2	x	x	..	..	..	..	..	..
Nodosaria affinis	..	..	x	..	..	..	..	..	..	..	..	..	..
Nodosaria limbata	..	..	..	..	x	x	..	..	x	..	..	..	x
Nodosaria obscura	1	x	..	..	..	..	..	..	..	..	..	..	..
Nodosaria prismatica	..	..	x	1	..	..	..	..	..	..	..	..	..
Palmula pilulata	..	..	..	1	2	x	..	..	..	..	..	..	..
Planularia sp.	..	..	..	..	..	6	..	..	3	..	..	..	x
Pyrulina sp.	..	..	..	..	..	..	..	x	x	..	x	..	..
Ramulina aculeata	2	..	x	1	..	..	x	x	..	x	x	x	..
Ramulina pseudoaculeata	..	x	..	1	2	x	..	..	..	x	7	4	x
Saracenaria sp.	..	..	3	..	..	..	..	..	..	..	..	..	..

Table 2—*continued*

Stratigraphic distribution of benthonic foraminifera in the reference section, Toolonga Calcilutite. Species are listed by superfamily as defined by Loeblich and Tappan (1988) and expressed as a percentage of the total benthonic foraminiferal assemblage. Stratigraphic thickness is given in metres above base of the Toolonga Calcilutite.

	UNIT 1		UNIT 2						UNIT 3				
	0.0	0.5	2.0	3.5	5.0	6.0	7.5	8.5	10.5	12.5	14.5	16.5	18.5
BOLIVINACEA													
Bolivinoides strigillatus	..	..	..	..	..	..	x	x	..	..	..	..	..
LOXOSTOMATACEA													
Loxostomum sp. cf. *L. eleyi*	..	..	..	1	2	x	x	x	x	x	..	..	..
EOUVIGERINACEA													
Eouvigerina sp. cf. *E. americana*	..	..	..	..	..	..	x	x	x	..	..	x	x
Eouvigerina gracillis	..	1	x	..	..	..	x	x	x	x	x	2	2
PLEUROSTOMELLACEA													
Ellipsoglandulina sp.	..	..	..	..	..	..	..	..	..	..	x	..	..
Ellipsoidella binaria	1	x	1	..	..	..	..	x	x	x	..	..	..
Ellipsoidella solida	1	x	..	..	..	..	..	x	..	x	x	..	..
TURRILINACEA													
Praebulimina reussi	..	..	..	..	2	x	x	x	x	x	x	x	x
Pyramidina szajnochae	7	38	1	12	x	2	11	26	9	x	..	..	..
DISCORBACEA													
Eponides concinna	x	10	11	4	7	7	x	6	9	9	16	7	25
Eponides diversus	1	3	..	4	..	12	..	..	..	x	7	7	8
PLANORBULINACEA													
Carpentaria conica	..	..	..	..	..	..	..	..	..	x	x	x	..
Carpentaria globosa	..	..	..	..	..	..	..	..	x	x	x	..	..
Cibicides excavata	..	..	..	..	..	..	x	x	3	x	x	..	..
Cibicides ribbingi	..	..	..	..	..	..	..	x	x	..	..	..	..
Cibicides sp.	..	..	..	..	..	..	x	x	x	..	..	..	..
ASTERIGERINACEA													
Nuttallinella coronula	..	..	..	..	..	..	x	x	x	..	..	..	..
NONIONACEA													
Pullenia cretacea	2	1	..	..	3	..	x	4	..	6	5	7	4
CHILOSTOMELLACEA													
Anomalinoides erikdalensis	6	1	1	13	31	4	x	15	19	28	29	32	30
Anomalinoides undulatus	46	8	2	4	7	x	..	..	..	..	..	..	..
Globorotalites micheliniana	x	x	..	..	..	..	15	x	..	..	..	..	..
Gyroidinoides noda	2	9	17	15	8	16	18	18	15	x	7	9	6
Lingulogavelinella insculpta	..	..	..	..	11	46	11	16	x	17	14	7	5
Lingulogavelinella sp.	..	..	..	..	x	..	..	..	..	..	..	..	..
Notoplanulina sp.	15	22	26	1	..	..	..	..	..	..	..	x	..
Osangularia sp.	..	..	..	..	..	6	29	..	15	7	..	..	..
Quadrimorphina allomorphinoides	..	..	..	..	x	..	x	..	x	x	x	..	..
Stensioeina truncata	..	..	..	..	x	..	..	..	..	..	..	..	..
Unidentified	1						x				x		x

in the section suggests that the youngest possible age for the section is within the *Globotruncana arca* zone (early Campanian). The presence of *Marthasterites furcatus* (Deflandre) in the highest sample taken from the reference section indicates that the section can be no younger than the *Aspidolithus parcus* zone (early Campanian).

Rate of sediment accumulation

The substrate was probably a thick planktonic foraminiferal / calcareous nannoplankton ooze by analogy to modern calcareous oozes. The oyster, *Pycnodonte gingninensis* Etheridge, normally an encrusting taxon, may have adapted to reclining in the soft substrate by the development of inflated valves. Other evidence includes the composition of the faunal assemblage, including taxa such as *Stensioeina* and *Bolivinoides* (foraminifera), *Inoceramus* (pelecypod) and trace fossils which are typical of soft bottom conditions (Reid 1962). An estimation of the rate of deposition can be made by correlation of the calcareous nannoplankton and planktonic foraminiferal biostratigraphy with the time scales given in Haq *et al.* (1987), although these correlations are subject to error given the number of direct comparisons available. The inferred rate of sedimentation, assuming a post-depositional compaction factor of 10% (estimated for European chalks by Scholle 1977) increases up the section and is calculated for each calcareous nannoplankton zone. The base of the *Reinhardtites anthophorus* zone was not recognized but the zone is assumed to be complete giving a depositional rate of 28 cm/million years. The *Lucianorhabdus cayeuxi* zone was recognized from 2-3.5 m in the reference section giving a depositional rate of 83-220 cm/million years. The *Calculites obscurus* zone was recognized from 3.5-5 m in the reference section giving a depositional rate of 110-220 cm/million years. The top of the *Aspidolithus parcus* zone was not recognized but the zone is assumed to be complete giving a depositional rate of 990-1 100 cm/million years. Hiatuses may be recorded in the reference section as (a) layers of phosphatic nodules (Figure 3) which Kennedy and Garrison (1975) and Kennett (1982) state are formed during periods of low or negative sedimentation or (b) *Inoceramus* rich horizons which may have formed as lag deposits.

Bathymetry

The presence of glauconite and phosphate within the section can be used to infer bathymetry. Bromley (1967) states that warm shallow water between 30 m and 300 m is particularly favourable for phosphate formation. Glauconite accumulates in modern oceans between 75 and 500 m, and mostly between 100 and 200 m (Odin and Stephen 1982).

Characteristics of the foraminiferal assemblage also were used for bathymetric determinations. The use of Cenozoic benthonic foraminifera in delineating bathymetry has been extensively documented but there are few studies of pre-Cenozoic bathymetric zonation because the significance of taxa is uncertain. Bathymetric models at the generic and species level for the Cretaceous are based on the homeomorphic comparison of Cretaceous and recent forms. The known bathymetric trends of Cretaceous species and genera were compared to the abundance groupings of benthonic foraminifera described in this study to assist in the determination of bathymetric conditions. Benthonic foraminifera indicate that deposition occurred in an epicontinental sea no shallower than ca. 100-200 m (outer neritic depths) and no deeper than ca. 200-500 m (upper bathyal depths). [It should be noted here that the terms outer neritic and upper bathyal are used to describe a bathymetric range and should not be confused with outer shelf and upper slope conditions because the Toolonga Calcilutite was deposited on a flat-lying epi-continental marine plain.] At the commencement of deposition, upper bathyal conditions prevailed. A decline in depth to outer neritic conditions, as shown by the foraminiferal assemblage, occurred about 6.0 m above

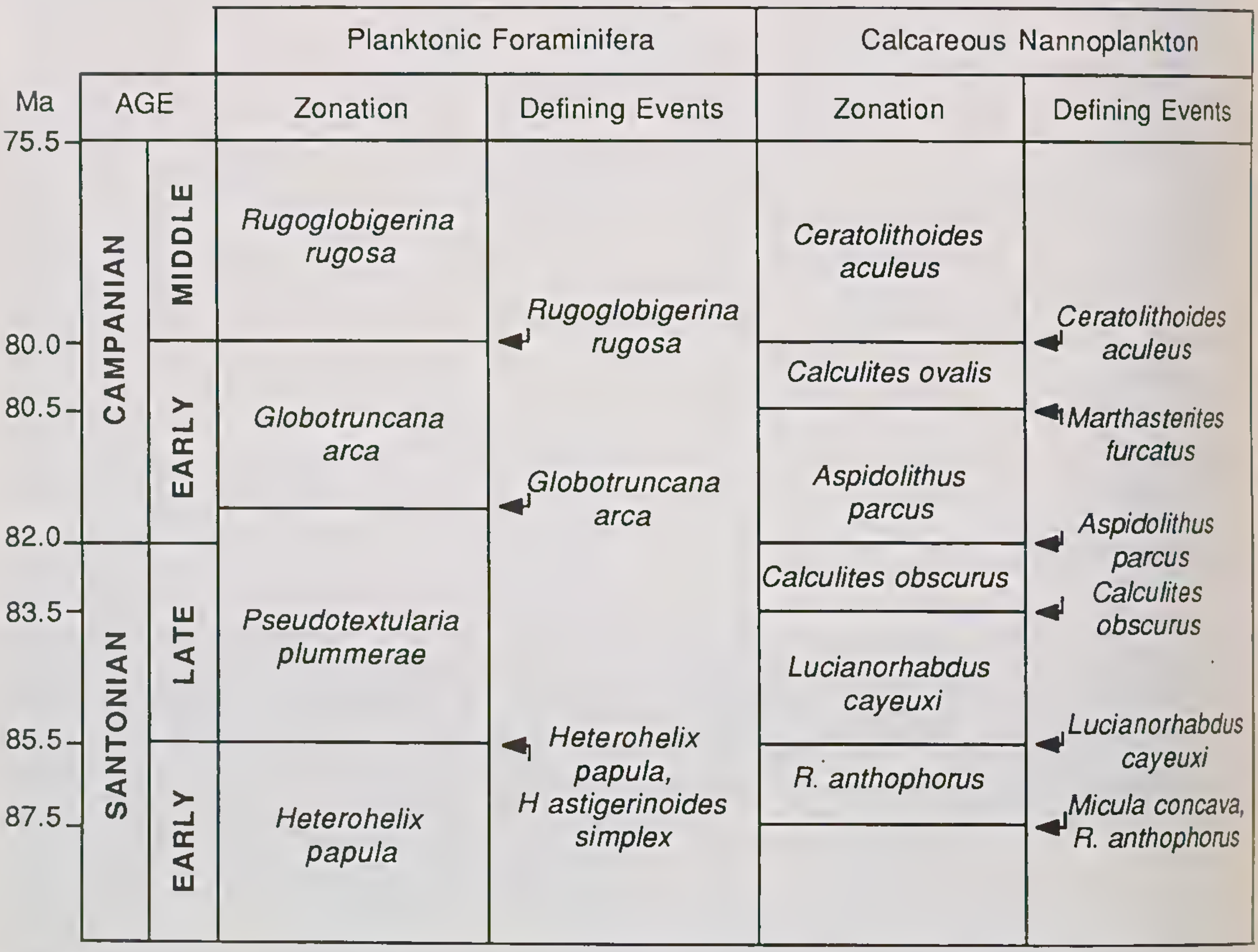

Figure 5 Planktonic foraminiferal and calcareous nannoplankton zonation used in this paper (after Rexilius 1984, pers. comm. 1988 and Sissingh 1977) with reference to radiometric dates given in Haq et al. (1987). (first appearance, last appearance).

the base of the section, coinciding with a rapid increase in the rate of deposition. Depth of deposition increased to upper bathyal from 10.5-14.5 m and then gradually declined to outer neritic depths thereafter. Rescrictions on the depth of deposition are evident from a study of the tectonics of the area. The Tooloonga Calcilutite was deposited on a passive margin and therefore the depth of deposition was controlled by eustatic sea level rises, which were shown by Haq *et al.* (1987) to be in the range of 180-250 m for the Santonian–Campanian interval.

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References

Ames L L Jr 1959 The genesis of carbonate apatites. Econ Geol 54:829-841.

Bromley R G 1967 Marine phosphorites as depth indicators. Mar Geol 5:503-509.

Bromley R G & Ekdale A A 1983. Flint and fabric in the European Chalk. In: (eds Sieveking G de G & Hart M B) The Scientific Study of Flint and Chalk. Proceedings of the Fourth International Flint Symposium, 71-83.

Clarke E de C & Teichert C 1948 Cretaceous stratigraphy of the lower Murchison River area, Western Australia. J Roy Soc W Aust 32:19-48.

Clayton C J 1983 The chemical environment of flint formation in Upper Cretaceous chalks. In: (eds Sieveking G de G & Hart M B) The Scientific Study of Flint and Chalk. Proceedings of the Fourth International Flint Symposium, 44-54.

Condon M A 1968 The geology of the Carnarvon Basin, Western Australia, Part 3 : post-Permian stratigraphy; structure; economic geology. Bull Bur Min Res Aust Geol Geophys 77(3):1-68.

Copp I A 1987 Stratigraphy and Palaeontology of the Gearle Siltstone, Lower Cretaceous, Carnarvon Basin, Western Australia. B Sc (Hon) Thesis Univ W Aust (unpubl).

Felder P J 1983 Rhythms, flint and mesofossils in the Cretaceous (Maastrichtian) of Limburg, The Netherlands. In: (eds Sieveking G de G & Hart M B). The Scientific Study of Flint and Chalk. Proceedings of the Fourth International Flint Symposium, 84-87.

Feldtmann F R 1963 Some pelecypods from the Cretaceous Gingin Chalk, Western Australia, together with descriptions of the principal chalk exposures. J Roy Soc W Aust 46(4):101-125.

Hancock J M 1975 The petrology of the chalk. Proc Geol Ass 86(4):499-535.

Haq B U, Hardenbol J & Vail P R 1987 Chronology of fluctuating sealevels since the Triassic. Science 235:1156-1166.

Hocking R M, Moors H T & van de Graaff W J E 1987 Geology of the Carnarvon Basin, Western Australia. Geol Surv W Aust Bull 133:1-289.

Jarvis I 1980 Geochemistry of phosphatic chalks and hardgrounds. J Geol Soc London 137:705-721.

Johnstone D, Condon M A & Playford P E 1958 The stratigraphy of the Lower Murchison River area and Yaringa North Station, Western Australia. J Roy Soc W Aust 41(1):13-17.

Johnstone D & Playford P E 1955 Geology of the Shark Bay—Murchison River area, Carnarvon Basin. W Aust Petr Pty Ltd Report (unpubl).

Kennedy W J & Garrison R E 1975 Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England. Sedimentology 22:311-386.

Kennet J 1982 Marine geology. Prentice Hall Inc., New Jersey. 318pp.

Lynch D A 1988 Lithostratigraphy, biostratigraphy and depositional environment of a reference section in the type area of the Toolonga Calcilutite, Carnarvon Basin, Western Australia. B Sc (Hon) Thesis Univ W Aust (unpubl).

Maliva R G & Siever R 1988 Diagenetic replacement controlled by force of crystallization. Geology 16:688-691.

Nyong E E & Olsson R K 1984 A palaeoslope model of Campanian-Maastrichtian foraminifera in the North American Basin and adjacent continental margin. Mar Micro 8:437-477.

Odin G S & Stephan J F 1982 The occurrence of deep water glaucony from the eastern Pacific : the result of in situ genesis or subsidence ? In: Watkins J S, Moore J C, *et al.* Deep Sea Drill Proj Initial Rep 66:419-428.

Olsson R K 1977 Mesozoic foraminifera—Western Atlantic. In: Stratigraphic Micropaleontology of Atlantic Basin and Borderlands. Developments in Paleontology and Stratigraphy 6:205-230.

Playford P E, Cockbain A E & Low G H 1976 Geology of the Perth Basin, Western Australia. Geol Surv W Aust Bull 124:1-311.

Rankin I A 1987 Selective dissolution of Upper Cretaceous foraminifera of the Gingin Chalk, Perth Basin, Western Australia. B Sc (Hon) Thesis Univ W Aust (unpubl).

Reid R E H 1962 Relationships of fauna and substratum in the palaeoecology of the Chalk and Chalk Rock. Nature 194:276-277.

Rexilius J P 1984 Late Cretaceous foraminiferal and calcareous nannoplankton biostratigraphy, southwestern Australian margin. Ph.D Thesis Univ W Aust (unpubl).

Rhoads D C & Morse J W 1971 Evolutionary and ecological significance of oxygen-deficient marine basins. Lethaia 4:413-428.

Savdra C E & Bottjer D J 1986 Trace fossil model for the reconstruction of palaeo-oxygenation in bottom waters. Geology 14:3-6.

Scholle PA 1977 Chalk diagenesis and its relation to petroleum exploration : Oil from chalks, a modern miracle ? Am Ass Pet Geol Bull 61(7):982-1009.

Sissingh W 1977 Biostratigraphy of Cretaceous calcareous nannoplankton. Geol Mijnbouw 56(1):37-65.

Sliter W V & Baker R A 1972 Cretaceous bathymetric distribution of benthic foraminifers. J For Res 2(4):167-183.

Appendix

The following list of foraminiferal and calcareous nannoplankton species present in the Toolonga Calcilutite is given in alphabetical order. The specimens listed here are housed in the Micropalaeontological Collection, Geology Department, University of Western Australia.

Benthonic Foraminifera

Ammobaculites sp. A
Ammobaculites sp. B
Ammodiscus cretacea (Reuss)
Anomalinoides erikdalensis (Brotzen)
Anomalinoides undulatus Belford
Astacolus sp. A
Astacolus sp. B
Berthelinopsis sp.
Bolivinoides strigillatus (Chapman)
Bullapora laevis (Sollas)
Carpentaria conica (Belford)
Carpentaria globosa (Belford)
Cibicides sp.
Cibicides excavata Brotzen
Cibicides ribbingi Brotzen
Citharina geisendorferi (Franke)
Citharina multicostata d'Orbigny
Citharina suturalis (Cushman)
Clavulinoides trifidus Belford
Dentalina admodicostata Belford
Dentalina marcki Reuss
Dorothia bulleta (Carsey)
Ellipsoglandulina sp.
Ellipsoidella binaria Belford
Ellipsoidella solida (Brotzen)
Eouvigerina sp. cf. *E. americana* Cushman
Eouvigerina gracilis Cushman
Eponides concinna Brotzen
Eponides diversus Belford
Frondicularia costulifera Belford
Frondicularia disjuncta Belford
Frondicularia mucronata Reuss
Frondicularia planifolium Chapman
Frondicularia teuria Finlay
Frondicularia verneuiliana d'Orbigny
Gaudryina sp. cf. *G. laevigata* Franke
Globorotalites micheliniana (d'Orbigny)

Globulina sp.
Glomospirella sp.
Goësella chapmani Cushman
Gyroidinoides noda (Belford)
Haplophragmoides sp. cf. *H. kirki* Wickenden
Laevidentalina sp.
Laevidentalina cylindroides Reuss
Laevidentalina gracilus (d'Orbigny)
Laevidentalina luma Belford
Lagena sp.
Lagena hexagona (Williamson)
Lenticulina sp.
Lenticulina macrodiscus (Reuss)
Lenticulina rotulata Lamarck
Lenticulina sublobatus (Reuss)
Lingulogavelinella sp.
Lingulogavelinella insculpta (Belford)
Loxostomum eleyi (Cushman)
Marginulina sp.
Marssonella oxycona (Reuss)
Neoflabellina praereticulata Hilterman
Neoflabellina rugosa (d'Orbigny)
Nodosaria affinis Reuss
Nodosaria limbata d'Orbigny
Nodosaria obscura Reuss
Notoplanulina sp.
Nuttallinella coronula (Belford)
Osangularia sp.
Palmula pilulata Cushman
Planularia sp.
Praebulimina reussi (Morrow)
Pullenia cretacea Cushman
Pyramidina szajnochae (Gryzbowskii)
Pyrulina sp.
Quadrimorphina allomorphinoides (Reuss)
Ramulina aculeata (d'Orbigny)
Ramulina pseudoaculeata (Olsson)
Saracenaria sp.
Silicosigmoilina sp.
Spiroloculina cretacea Reuss
Spiroplectammina gryzbowskii Frizzell
Spiroplectammina laevis (Roemer)
Spiroplectammina paula Belford
Spiroplectinata compressiuscula (Chapman)
Stensioeina truncata Belford
Verneuilina parri Cushman

Planktonic Foraminifera

Archaeoglobigerina cretacea (d'Orbigny)
Costellagerina bulbosa (Belford)
Globigerinelloides alvarezi (Eternod Olvera)
Globotruncana sp.
Globotruncana arca (Cushman)
Globotruncana bulloides Vogler
Globotruncana fornicata (Plummer)
Globotruncana linneiana (d'Orbigny)
Globotruncana ventricosa White
Hastigerinoides simplex (Morrow)
Hedbergella sp. aff. *H. planispira* (Tappan)
Heterohelix globulosa (Ehrenberg)
Heterohelix moremani (Cushman)
Heterohelix papula (Belford)
Whiteinella paradubia (Sigal)

Calcareous Nannoplankton

Aspidolithus parcus (Stradner)
Calculites obscurus Deflandre
Lucianorhabdus cayeuxi Deflandre
Marthasterites furcatus (Deflandre)
Micula concava (Stradner)
Reinhardtites anthophorus (Deflandre)